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ORIGINAL RESEARCH

SPATIOTEMPORAL COMPARISON OF OVERGROUND AND TREADMILL RUNNING WITH PRESSURE SENSOR INSOLES IN DIVISION I COLLEGIATE RUNNERS

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ABSTRACT

Study Design: Repeated measures

Background: Both clinicians and researchers often utilize treadmills to analyze spatiotemporal and biomechanical factors during running. However, there is question of whether or not treadmill running mimics overground running. The development of new wearable technology, such as pressure sensor insoles, presents an opportunity to compare the two running conditions.

Purpose: To compare the spatiotemporal factors between overground and treadmill running in collegiate runners, using pressure sensor insoles.

Methods: Twenty-one collegiate runners (age 20.1 $\pm$ 1.5 years, 81% female) were recruited from a Division I Cross Country team. Subjects participated in two 15-minute testing sessions. During the first session, subjects ran at their "easy run pace" for 200 meters, while wearing pressure sensor insoles. During the second session, subjects ran at a speed-matched pace on a treadmill for one minute at a level grade, and one minute at a 1% incline. Cadence, stance duration and swing duration were processed using Moticon Science Pro+ software (Munich, DE). Data between overground and treadmill running was compared using repeated measures analysis of variance with $\alpha = 0.05$.

Results: Compared to overground running, level and incline treadmill running was associated with increased cadence (mean difference [MD]=3.55-3.22 strides per minute; $p < 0.01$), decreased stance duration (MD=14-16 ms; $p < 0.01$), and decreased swing duration (MD=11-12 ms; $p < 0.05$).

Conclusion: In collegiate runners, overground and treadmill running differ in spatiotemporal comparisons.

Levels of Evidence: 3

Key Words: Cadence, cross country, pedobarometry, running injury, movement system

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INTRODUCTION

Overuse injuries are unfortunately common in runners. The overall incidence of running-related injuries (RRI) ranges from 7.7 to 17.8 per 1000 exposure hours.[1] Many extrinsic risk factors have been hypothesized to contribute to RRIs, such as training error, running surface, and running mode.[2-4] Intrinsic risk factors such as genetics, biomechanical and spatiotemporal running variables have also been investigated.[2,5,6]

Spatiotemporal factors of running include stride length, speed, cadence, stance duration and swing duration. A complete stride cycle typically consists of 30-35% stance phase and 65-70% swing phase.[7] Stance duration, also known as ground contact time, is inversely proportional to running speed, while swing duration is directly proportional to speed.[7] Cadence, defined as number of strides per minute, can affect running mechanics, such as stride length,[8] tibial acceleration,[9] and foot inclination angles,[9] thus altering braking forces and overall stresses to the lower extremity.[10,11] These changes are thought to affect the distribution of forces in the foot, knee, and hip, which can have implications for therapeutic settings.[5,12]

Treadmills serve as a useful tool for both clinicians and researchers. Clinicians can utilize treadmills for gait analysis and gait retraining. Due to advancements in video technology, clinicians can analyze various 2D kinematic and spatiotemporal data during treadmill running.[13] Additionally, treadmills are a common platform for gait retraining, such as cadence training[9,11,14] and various motor learning strategies.[15-17] Researchers also utilize instrumented treadmills for running analysis.[18] However, there is question of whether or not treadmill running resembles overground running. Several authors have found both similarities and differences in biomechanical and spatiotemporal factors between the two running conditions.[12,18-21] Yet, several limitations confound the comparison of overground versus treadmill running, as described below.

Investigators have faced challenges in consistently measuring natural running form during overground running. For example, Riley et al[19] and Cronin et al[21] implemented short, 15-meter runways, which reduced the likelihood that participants ran with natural, "steady state" technique. Researchers have also reported variability in intra- and inter-trial running speeds, and when matching running speeds between overground and treadmill running.[19-22] Furthermore, there is risk of a "targeting effect," in which subjects alter their technique to aim for the force plates.[23] Due to these limitations, more research is needed to validate the previous claims comparing these running conditions. Finally, there is some speculation that treadmill running with approximately 1% incline mimics overground running better than level treadmill running, but the authors are not aware of any studies that support this claim.

Wearable technologies such as plantar pressure sensor insoles, present a novel, unique method to compare natural running patterns in unrestricted environments with treadmill-based assessments.[24] The Moticon wireless pressure sensor insoles (Moticon Science, Munich, DE, Figure 1) have been developed with a minimalistic design to allow subjects to move without constraints in a natural environment. Measurement reliability and validity for these insoles have been previously reported for walking and running gait. [25,26] Temporal parameters of walking gait using these devices have excellent concurrent validity against the instrumented treadmill for cadence (95% limits of agreement [LoA] = -1.39 to 1.39 steps/min), right stance duration (LoA = -35 to 17 ms), and left stance duration (LoA = -33 to 18ms),

Figure 1. *Moticon pressure sensor insoles.*

as well as excellent test-retest reliability (ICC = 0.91-0.93).[25] Additionally, stance duration during walking and running gait has been validated against AMTI force plates (r = 0.86-0.94, LoA = 3 to 12%) and PedarX sensor insoles (r = 0.65-0.94, LoA = 4 to 12%).[26]

Pressure sensor insoles may address some of the challenges that treadmill running creates for researchers and clinicians. While some sensor insoles have been shown to be valid and reliable, few research studies have utilized these novel devices to compare biomechanical and spatiotemporal factors between overground and treadmill running. This research aims to compare the spatiotemporal factors between overground and treadmill running in collegiate runners, using pressure sensor insoles.

METHODS

Design

The cohort study utilized a repeated measures design to compare spatiotemporal properties of running overground, on treadmill, and treadmill at 1% incline. The study was approved by the Institutional Review Board (IRB) at the University of South Dakota (USD). All subjects signed an IRB-approved informed consent form prior to participation.

Subjects

Subjects were recruited from the USD Division I Men's and Women's Cross-Country team. Exclusion criteria included inability to run due to injury or illness at the time of data collection.

Instruments

The Moticon wireless plantar pressure sensor insoles contain 13 capacitive pressure sensors that cover 52% of the insole area and create minimal disruption to the foot-shoe interface.[25] Data were recorded at a sampling frequency of 50 Hz. Five pairs of insoles were used, ranging from US men's sizes 5.5-11.5.

Data Collection

Subjects underwent two, 15-minute testing sessions, each two days apart. Subjects were instructed to wear the same pair of their personal running shoes during both sessions to ensure consistency of measurement. During the first testing session, subjects participated in a 5-minute dynamic warm-up routine, consisting of a 200-meter jog, A-skips, B-skips, high knees, and butt kickers. Size-matched sensor insoles were placed in the subjects' shoes, replacing any sock liner or foot orthosis, in order to record spatiotemporal data. Subjects were instructed to run one lap around a 200-meter indoor track at the pace they would run on long-distance runs, termed "easy run pace." During the middle, straightaway portion of the run, a 50-meter time was recorded using a laser timing system (PowerMax Speed Timer, USA) and converted into a treadmill running speed (miles per hour) using the equation $[\frac{50}{time(\text{seconds})} * 2.237]$. Subjects then completed a post-test questionnaire that included perceived impact of the sensor insoles (Figure 2).

How did running in the pressure sensors feel, compared to your normal running?

Same as normal running	Minimally different	Moderately different	Extremely different
0	1	2	3

How did running in the pressure sensors affect your running form, compared to your normal running?

Same as normal running	Minimally different	Moderately different	Extremely different
0	1	2	3

Figure 2. *Post-test questionnaire items rating the subjects' perceived comfort and impact of sensor insoles.*

During the second testing session, subjects underwent a similar, standardized warm-up. After this, subjects walked on a treadmill (Woodway Pro, Waukesha, WI, USA) at 3.0 mph for one minute in order to acclimate to the treadmill. Next, they ran for one minute at their matched, "easy run pace," according to the speed conversion from the first testing session. Finally, the treadmill incline was increased to a 1% grade, and subjects ran for another minute at the same speed. Following testing, they completed a second post-test questionnaire.

All gait-related data were processed using Moticon Science Pro+ software (Moticon, Munich, DE). The Gait Report Function synthesized running data for the three running conditions: overground (track), treadmill at 0% incline, and treadmill at 1% incline. This function calculates spatiotemporal (i.e. cadence, swing and stance time) and kinetic data (i.e. center of pressure progression, foot pressure distributions, rate and magnitude of force development). In order to maintain consistency of data, a six-second clip was processed during the middle portion of each run.

Data Analysis

Spatiotemporal data were analyzed using SPSS Statistics 24.0 Software (IBM, NY, USA). The Shapiro-Wilk test was conducted to test for normality. Descriptive statistics of the perceived impact of insoles were obtained. A one-way repeated measures analysis of variance (ANOVA) with Bonferroni post-hoc analysis was conducted to evaluate the null hypothesis that there were no significant differences in spatiotemporal variables between the three running conditions. Statistical significance was set at $\alpha = 0.05$.

RESULTS

Data from twenty-one of 23 experienced, collegiate runners (age 20.1 ± 1.5 years, 81% female, 5.8 ± 3.9 collegiate seasons) were analyzed for this study. One subject was excluded from analysis due to technical difficulties with data acquisition. Furthermore, the Shapiro-Wilk test revealed an abnormal sample distribution for the right swing phase of overground running ($W = 0.67$, $p < 0.01$). Visual observation using the Q-Q plot and boxplot revealed one outlier due to a data processing error. After the outlier was removed from data analysis, all sample distributions fell within acceptable ranges.

Descriptive statistics including gender, age, body mass index, running experience, injury, and footwear, are provided in Table 1. Table 2 provides descriptive statistics of survey responses of patient-perceived sensor insole impact on comfort and running technique. Subjects perceived minimal discomfort while wearing the sensor insoles during the first (1.0 ± 0.7) and second (0.9 ± 0.8) testing sessions. Running technique was minimally impacted during the first (0.7 ± 0.6) and second (0.7 ± 0.7) sessions.

Table 1. *Descriptive statistics (n = 21).*

Gender	17 (81%) female 4 (19%) male
Age (years)	20.1 ± 1.5
BMI (kg/m^2)	20.1 ± 1.6
# of collegiate competitive seasons*	5.8 ± 3.9
% with injury history	90%
% currently running without any injury	76%
Shoe type	71% neutral 29% stability
% who currently wear foot orthoses	38%
% who have worn foot orthoses over lifetime	62%
Running speed (mph)†	10.1 ± 0.9
Running speed (m/s)†	4.5 ± 0.4

* - Seasons competed during collegiate career, including cross country, indoor track & field (T&F), and outdoor T&F. A runner could compete in three seasons each academic year.
† - Calculated during 50-meter overground running trial.

Spatiotemporal descriptive statistics and ANOVA results are reported in Tables 3 & 4, respectively. Running overground, treadmill at 0%, and treadmill at 1% incline had statistically significant effects on cadence ($F = 47.0$, $p < 0.01$), stance duration ($F = 17.2$-18.8, $p < 0.01$), and swing duration ($F = 4.2$-6.7, $p < 0.05$). Figure 3 compares the mean cadence, stance and swing duration in each runner during the three running conditions. When compared to running overground, cadence increased by 3.55 strides per minute ($p < 0.01$) during 0% treadmill running and 3.22 strides per minute ($p < 0.01$) during 1% treadmill running. However, there was no statistically significant difference in cadence between 0% and 1% treadmill conditions. Subjects also had significantly reduced stance duration on right and left limbs during 0% treadmill running (mean difference: R 15 ms; L 16 ms, $p < 0.01$) and 1% treadmill running conditions (mean difference: R 15 ms; L 14 ms, $p < 0.01$). No statistically significant difference

Table 2. *Survey responses to perceived impact of sensor insoles during running. Reported as mean rating, ± SD.*

	Session 1 (overground)	Session 2 (treadmill)
How did running in the pressure sensors feel, compared to your normal running?	1.1 ± 0.7	0.9 ± 0.8
How did running in the pressure sensors affect your running form, compared to your normal running?	0.7 ± 0.6	0.7 ± 0.7

Key: 0=same as normal running; 1=minimally different; 2=moderately different; 3=extremely different

Table 3. *Descriptive statistics of spatiotemporal values while running overground, treadmill at 0%, and treadmill at 1% incline. Reported as mean ± SD, except Stance:Swing, reported as a ratio.*

	Overground (track)	Treadmill, 0% incline	Treadmill, 1% incline
Cadence, strides per minute	87.8 4.6	92.4 ± 6.4	92.1 ± 5.9
Right stance duration, ms	202.3 ± 21.6	187.3 ± 22.7	187.7 ± 16.9
Left stance duration, ms	200.0 ± 19.0	183.6 ± 19.4	186.4 ± 20.1
Right swing duration, ms	479.5 ± 31.4	468.1 ± 36.4	471.0 ± 33.0
Left swing duration, ms	482.7 ± 36.3	467.3 ± 38.4	467.7 ± 37.2
Stance:swing ratio	29:71	28:72	28:72

Table 4. *Mean differences in spatiotemporal parameters while running under three conditions: overground (OG), treadmill with 0% incline (TM0), and treadmill with 1% incline (TM1). Results are based on estimated marginal means from ANOVA.*

Variable	Condition A - B	Mean Difference A - B	Std. Error	Sig.†	95% Confidence Interval for Difference†	
					Lower Bound	Upper Bound
Cadence (strides per minute)	OG - TM0	-3.6	0.4	<.01*	-4.7	-2.4
	OG - TM1	-3.2	0.3	<.01*	-4.1	-2.4
	TM0 - TM1	0.3	0.2	.58	-0.3	1.0
Right stance duration (ms)	OG - TM0	15	3	<.01*	8	22
	OG - TM1	15	3	<.01*	7	23
	TM0 - TM1	0	3	1.00	-7	7
Left stance duration (ms)	OG - TM0	16	3	<.01*	9	23
	OG - TM1	14	3	<.01*	7	20
	TM0 - TM1	-2	2	.61	-7	2
Right swing duration (ms)	OG - TM0	11	4	.02*	1	22
	OG - TM1	9	3	.07	0	18
	TM0 - TM1	-3	3	.80	-9	4
Left swing duration (ms)	OG - TM0	12	3	<.01*	3	20
	OG - TM1	11	3	.01*	2	20
	TM0 - TM1	-1	3	1.00	-8	6

* - The mean difference is statistically significant at the $p < 0.05$ level.
† - Adjustment for multiple comparisons: Bonferroni.

in stance duration was identified between 0% and 1% treadmill conditions. Significant reductions in right and left swing duration were observed during 0% treadmill running (mean difference: R 11 ms; L 12 ms, $p < 0.05$) and only left swing duration for 1% treadmill running (mean difference: L 11 ms, $p < 0.05$). Right swing duration under the 1% condition showed a trend toward reduction, but the difference was not significant ($p = 0.07$). No significant difference in swing duration was found between the two treadmill conditions.

DISCUSSION

Compared to overground running, treadmill running was associated with significant changes in spatiotemporal running factors, including increased cadence, decreased stance duration, and decreased swing duration. Riley et al[19] found similar changes during treadmill running in 20 healthy, young subjects, such as increased cadence (mean difference = 2.39 strides per minute, $p < 0.01$), decreased stride time, and decreased stride length. Comparatively, the cadence difference in this study (3.55-3.22

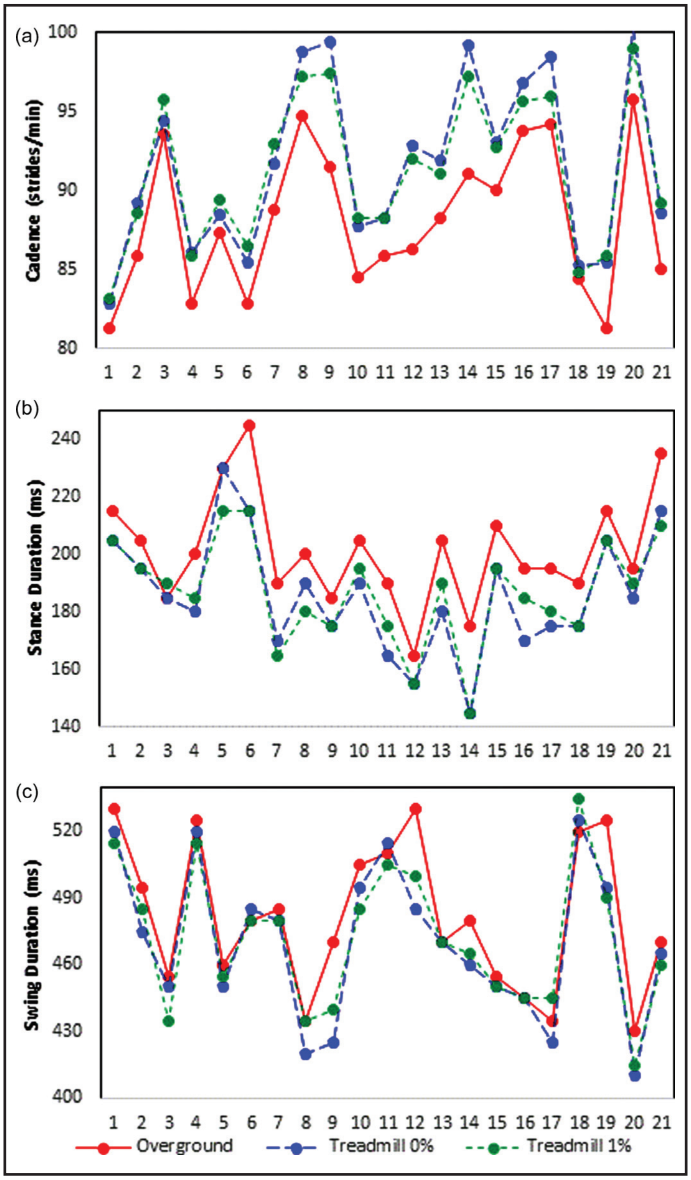

Figure 3. *Means of each individual runner during the three running conditions, including (a) cadence, (b) stance duration, and (c) swing duration.*

strides per minute) was nearly fifty percent greater. The difference may be associated with running speed. Subjects in this study ran approximately 0.7 m/s faster (4.5 m/s vs 3.8 m/s) than the subjects examined by Riley et al,[19] thus it is plausible that the increased running speed would lead to greater increases in cadence.

Contrary to results in this study, other authors reported disparate associations between running conditions. Hong et al[20] found that in 16 male collegiate runners, treadmill running stance duration did not change, while Garcia-Perez et al[27] found that in 27 healthy recreational runners, treadmill running cadence did not change but stance duration increased. Key differences in methodology may explain the contradicting results. For example, both Hong et al[20] and Garcia-Perez et al[27] regulated the running speeds (3.8 and 3.3-4.0 m/s, respectively), while this study permitted self-selected running speeds (4.5 $\pm$ 0.4 m/s). Furthermore, Garcia-Perez et al[27] used a robust insole system with additional equipment, such as ankle and waist units, straps, and cables, which likely affected running mechanics.[28] Additionally, Kluitenberg et al[18] and Willy et al[12] found no significant differences in stance duration, but these differences may be due to testing on a short runway (17.5-m and 25-m, respectively) and intratrial variability in running speeds. Kluitenberg et al[18] calculated running speed based on a short, 2.5-meter time, compared to a 50-meter time measured in this study. Willy et al[12] allowed for 3% variability in running speed between overground and treadmill conditions, while this study standardized the exact speed. Lastly, for all studies analyzing overground running with a force plate, a "targeting effect" could have significantly altered the subjects' mechanics of a natural, steady state step while stepping over the force plate. Thus, differences in methodology may have led to divergent results.

Nonetheless, most of the results from aforementioned studies suggest that treadmill running alters spatiotemporal factors when compared to overground running.[12,19,20,27] One reason for this could be error in treadmill running speed calibration. Anecdotally, the majority of subjects in this study expressed that the treadmill running speed, though converted from a reliable overground running time, felt significantly faster. These comments are similar to those reported by Rozumalski et al,[22] who discussed unanimous complaints that the overground-matched speeds were too fast when running on the treadmill. Kong et al[29] also found that subjects ran 27.1% slower on treadmill than overground, when asked to match their preferred speed between the two conditions. Biomechanically, running speed is increased by increasing step rate and step length. The collegiate runners in this study consistently adapted to the "faster" treadmill speeds by increasing step rate (increasing cadence, decreasing stance and swing duration). Unfortunately, data on step length was unable to be collected in the current study, which would have provided a more comprehensive spatiotemporal analysis.

This study is the first to investigate the relationship between overground running and treadmill running at 0% and 1% incline. The results suggest that spatiotemporal factors are no different when running at 0% and 1% incline, therefore challenge the preconceived notion that a 1% incline mimics overground running better than level treadmill running. However, this study did not analyze running kinetics, kinematics, or physiologic factors, so the results should be interpreted with caution. Despite similar spatiotemporal factors, no conclusion can be made about whether a 1% incline running affects plantar loading, joint angles, muscle activation, or cardiovascular stress differently than level treadmill running. A study by Swanson et al[30] calculated that treadmill running at 4.5 m/s on a 30% incline facilitated higher muscle activation during both stance and swing phases, compared to level running. It is possible that the degree of inclination may play a role in the task-specific biomechanical effects, and a minimal inclination increase (1%) may not stimulate significant, detectable changes in running. Nonetheless, future studies should compare other biomechanical and physiologic factors between overground, level treadmill, and various degrees of incline treadmill running.

With the growing popularity of treadmill running analysis and interventions, clinicians and researchers must competently discern the appropriate utilization of treadmill running. Indeed, many similarities between overground and treadmill running have been reported.[12,18,19,31] However, this study explores some key differences: cadence, stance duration, and swing duration. These noteworthy results have significant clinical implications. For example, if cadence is different between the two running conditions, then the carryover effects of cadence training from treadmill to overground running should be questioned. Future research should continue to investigate spatiotemporal comparisons in healthy and injured populations. At a minimum, all stakeholders should consider the current state of overground and treadmill running comparisons to be incomplete and continue exploring research to seek best practice.

Limitations

These results are generated from a small sample size. Data from two of 23 subjects were excluded from the study, which may have impacted the results. Data from male and female runners were not differentiated and could be explored in future research. Additionally, the direct effect of insole devices on running mechanics is still under investigation. The Moticon sensor insoles used in this study comprised a minimalist system (only the insoles), fitting five insole sizes to a range of shoe sizes. Thus, the insole design and shoe-fit compatibility may have impacted running technique, but the questionnaire responses suggest that the insoles created minimal discomfort or alteration of running technique (Table 2). In order to reduce the bulk, however, the current Moticon sensor insole system is limited by the low number of pressure capacitors (13) and sampling frequency (50 Hz), which may affect data processing.[26] Future advancements in technology, allowing for a larger quantity of capacitors and higher sampling frequency, will permit more accurate measurements in order to better analyze running. The study used a fixed design of running overground, followed by running on a treadmill, so the impact of sequencing cannot be overlooked. Finally, the subjects were experienced, collegiate runners, which may suggest altered treadmill accommodation strategies leading to different effects on spatiotemporal running factors. Therefore, these results must be interpreted with caution when generalizing to novice and/or recreational runners.

CONCLUSION

The results of the current study suggest that in collegiate runners, overground and treadmill running differ in some spatiotemporal comparisons. Therefore, clinicians and researchers should use caution when extrapolating data between overground and treadmill running conditions.

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